A REVIEW OF THE PROGRESS OF ASTRONOMY*

By J. S. Plaskett

In view of the injunctions of the secretary of this division, Professor Luck, who asked me to take part in this symposium, and who suggested that it would be preferable to deal comprehensively with one phase of the science rather than wander over the whole field and that it was not necessary to limit the discussion to work done at Pacific Coast observatories, I have selected for review the most engrossing subject now engaging the attention of the mathematical sciences, the subject of the expansion of the Universe. Although I have no mathematical qualifications for such a review, that is perhaps not wholly an objection for a general audience, as I must perforce then express myself in language understandable by the great majority of my hearers, whereas if mathematically expressed probably less than five per cent could successfully follow my arguments. I took the precaution to inquire from Professor Houston, who is to review physics, whether he had any designs on the Universe, but he assured me that in the present confused state of the theoretical work, the astronomically observed fact of the increasing red-shift of the spectral lines with increasing distance of the nebulae is the only sure datum in the whole question.

You will note that I called this phenomenon the red-shift and did not describe it as representing the recession of the nebulae. The assumption that this line displacement is the result of an expansion of the Universe carries so many startling implications respecting the usually accepted time-scale of stellar evolution and has produced so much confusion and contradiction among the exponents of the various models of the space-time world evolved to explain this phenomenon, as to make it preferable, for astronomers at any rate, to hold fast to the observed fact that the spectral lines of the extra-galactic nebulae

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are displaced redward by an amount approximately proportional to the distance of the nebulae.

The splendid pioneer work of Slipher at the Lowell Observatory on the spectra of the extra-galactic nebulae, which has hardly received the attention it deserves, showed that out of 41 observed there were only 5 nebulae, all in one region of the sky, which had an apparent velocity of approach, later practically accounted for by the rotational velocity of the Sun in its orbital motion around the center of the galaxy. In the remaining 36 the spectral-line displacements were preponderatingly redward, corresponding to velocities of recession up to some 1800 kilometers per second for spiral and elliptical nebulae. These observations did not create any great theoretical commotion, although de Sitter's model of the space-time world did make some attempt at an explanation of the red-shifts which were, at the time of his discussion, not so preponderatingly present in the data as they have later become.

As is well known, Hubble, at the Mount Wilson Observatory, has for many years been investigating the distances and dimensions of the nearer extra-galactic nebulae from the luminosities of *Cepheids,* novae, and other stars. He has, further, developed methods of obtaining the distances of nebulae, which could not be resolved into stars, by means of apparent magnitudes and diameters and by other indirect methods. In 1929 in an important and suggestive paper in the *Proceedings of the National Academy of Sciences,* he showed clearly that the apparent radial velocities as measured by the spectral-line displacements of 24 extra-galactic nebulae, whose distances could be derived, were proportional to the distances, the numerical relation being a red-shift equivalent to a velocity of about 500 km/sec. for every million parsecs. This relation has recently been extended by Hubble and Humason by remarkable observational methods to various groups of nebulae at increasing distances, the results appearing in the *Astrophysical Journal* for July, 1931. The most distant nebula there discussed was the brightest member in Christie's cluster in *Leo,* whose distance was estimated as about 100,000,000 light-years and whose apparent velocity was 19,700 km/sec. More recently still two

nebulae in a cluster in *Gemini* have been observed which at a distance of about 135,000,000 light-years have a velocity of about 24,000 km/sec. Hubble and Humason's final conclusion is that there is an increase in the apparent velocity of recession of about 560 km/sec. for every million parsecs, or a distance of 3,260,000 light-years.

This remarkable relation, that the displacement of the lines of the nebulae is proportional to their distances, now seems established beyond reasonable question and admits of two fairly obvious explanations. Either this increasing red-shift is a Doppler effect and the Universe, or rather the part of it we can observe, is expanding at an alarming rate, or else the displacement is due to some atomic interaction which decreases the light-frequency proportionately to the distance of the source. Either explanation seems to involve relativistic mechanics.

When the observational relation was first put forward definitely by Hubble in 1929, the general trend of the tentative explanations advanced suggested that there was some mysterious process operating in the space-time world which slowed up the atomic clock, thus producing the red-shift. I distinctly remember being present at the meeting of this section of the American Association for the Advancement of Science at Berkeley in 1929, when no one appeared to have the temerity to suggest that Hubble's recently announced velocity-distance relation represented an actual recession of the nebulae.

Two hypotheses, suggesting that the observed shift is due to a decrease in frequency proportional to the distance, have been advanced by Zwicky and MacMillan, respectively. Zwicky, in 1929, considered several possible causes, other than velocity, of the red-shift of the spectral lines of the nebulae and put forward as a possible explanation a "gravitational drag of light." A light-quantum $h\nu$ has, according to the relativity theory, an inertial and gravitational mass $\frac{h\nu}{c^2}$. A quantum, therefore, passing a mass M will not only be deflected but will transfer momentum and energy to M. During the process the light-quantum will change its energy and hence its frequency and is accordingly a sort of gravitational analogue to the Comp-

ton effect. Zwicky computed the possible effect, which will obviously be a function of the distance and of the density of space. Taking Hubble's limits of the density $10^{-25} > \rho > 10^{-31}$ gm/cm^3, he obtains $\frac{\Delta\nu}{\nu}$ lying between the limits 3.10^{-2} and 3.10^{-7} per million parsecs, while Hubble's observed value of the red-shift is $1.9.10^{-3}$, an agreement in the order of magnitude.

The second hypothesis was advanced by MacMillan in a letter to *Nature* on January 16 this year. MacMillan suggests that the red-shift of the lines is due to the loss of energy by the photon in its long journey of millions of years. This loss of energy may be due either to inherent instability of the photon, or possibly to collisions with other photons and would be equivalent to a decline in frequency. MacMillan calculates on the hypothesis of energy leakage and on the basis of Hubble's velocity-distance relation that a light quantum loses one per cent of its energy in 5,400,000 parsecs. He states that "such an interpretation of the extraordinary shifts that are observed will be more acceptable to many than an interpretation which makes our galaxy a center from which all others are fleeing with speeds that are proportional to their distance." He is in error in assuming our galaxy as the only reference point, as the phenomenon will obviously be the same at every point in space. MacMillan is a well-known advocate of a very extended time-scale of stellar evolution, which will naturally make him object to the niggardly interval allowed by the theory of the expansion of the Universe.

I am not able to discuss adequately the validity of the assumptions involved in these two hypotheses on the origin of the red-shift. I think it is obvious, however, in view of the many difficulties connected with the expansion hypothesis, that they are at least worth considering, and while we have no definite evidence that the frequency of the light quantum may be diminished proportionately in its passage through great distances, the difficulties do not seem much greater than those encountered in the alternative theory of the expansion of the Universe.

Curiously enough I was also present in London at the May 1930 meeting of the Royal Astronomical Society when Eddington announced—the first time to my knowledge that it had been directly and unambiguously stated at an astronomical meeting—that the red-shift was due to the expansion of the Universe. Even then he did not express orally his conviction of the reality of this expansion so strongly as it was presented in the published paper or as it was echoed afterward by the mathematical physicists. It will be preferable, however, before giving Eddington's results, to discuss briefly and chronologically the earlier treatments of the relativistic space-time world. In describing the results obtained, the words of the authors are frequently closely adhered to, particularly when concise or characteristic.

It should be distinctly remembered, as Tolman has specifically stated, that "such problems of cosmogony are attacked by constructing conceptual models of the Universe. Such models are highly abstract and idealized as contrasted with the actual Universe, as indeed they have to be in order to treat them with the mathematics at our disposal." The assumptions and simplifications required are often not explicitly mentioned so that the results have frequently a fictitious reality, and this is obvious when it is realized how many different solutions based on the velocity-distance relation have been made and how confused and contradictory are the views of the highest authorities on the subject. It should not be forgotten, however, that it is by such tentative methods that progress is achieved and the only precaution needed is to remember that all these models of the Universe are probably greatly different from reality, and that they should not be taken too seriously. The only thing we are reasonably sure of is that the red-shift is approximately proportional to the distance within the region of space observed.

Acceding to the theory of relativity a homogeneous Universe may exist such that all positions in space are completely equivalent; there is no center of gravity. The radius of space R is constant; space is of uniform positive curvature $\frac{1}{R^2}$, and

the volume of space has a finite value, $\pi^2 R^3$. Straight lines are closed lines going through the whole of space without encountering any boundary and return to the origin after having traversed a path of length πR.

The first models proposed for the world are due to Einstein and de Sitter and are both static models, assuming no motions in the Universe.

a) *Einstein's world.*—This is a static model based on the equations of relativity and gives a relation between the supposedly uniform density and the radius R. This relation, however, includes the unknown and mysterious cosmical constant λ. This model has been the basis for some of the more recent models but has two objections. As it is static it can offer no explanation for the apparent recession of the nebulae, and, moreover, it requires a positive value of the cosmical constant λ to prevent the pressure from becoming negative. Although little is known of the value of λ, it must be a very small quantity.

b) *De Sitter's world.*—This model ignores the existence of matter and has zero density. The radius R is simply connected with the cosmical constant, $\frac{3}{R^2} = \lambda$. De Sitter found that, on one of two alternative relativity hypotheses, the light of very remote objects would be displaced toward the red as if they were receding from us. The difficulty of course lies in the emptiness of de Sitter's world where the introduction of galaxies would distort the resultant form of the equations. This model cannot account, therefore, for both the red-shift and the density of matter in space. It has been briefly said that Einstein's world contains matter and no motion, and de Sitter's contains motion and no matter.

These two models of the space-time world may be said to have held the field until the pressure produced by the increasing observations showing the preponderance of red-shifts in the nebulae and the direct linear relation between these shifts and the distance discovered by Hubble almost forced a modification. There were, however, two exceptions, two mathematical discussions both given before the velocity-distance relation

had been advanced, which gave expressions for a non-static world. The first of these was by Friedmann in 1922, but as he did not attempt any direct application of his results, it was not entirely satisfactory and received little attention. Nevertheless, he should be given credit as the originator of the non-static model. The other exception was the theory advanced by the Abbé Lemaitre of the University of Louvain in a paper in the *Annals of the Scientific Society of Brussels* in 1927. As this was long before the insistent demand for an explanation of the red-shift arose and before the discovery of the velocity-distance relation, and as the paper was buried in this little-read publication, it entirely escaped attention and was only later discovered by Eddington after he had started an investigation on a non-static model of the Universe.

Although Lemaitre made an arbitrary assumption as to the value of the cosmical constant λ and neglected the presence of radiation and the transformation of matter into radiation, still the development of a non-static model of the Universe intermediate between Einstein's and de Sitter's and the important result that the red-shift can be interpreted as an expansion of the Universe are due to him. Lemaitre's main results can be briefly summarized:

a) The radius of the Universe is a constant related to the cosmical constant by Einstein's relation

$$\sqrt{\lambda} = \frac{2\pi^2}{\varkappa M} = \frac{1}{R_0}$$

where $\varkappa = 1.87 . 10^{-27}$ C.G.S.

b) The radius of the Universe increases without limit from an asymptotic value R_0 (Einstein Universe) for $T = -\infty$.

c) The red-shift in the spectra of the spirals represents a velocity of recession caused by the expansion of the Universe.

Lemaitre computes the initial radius from his formulae and from Hubble's estimate of the density of space as $R_0 =$ 900,000,000 light-years.

The next stage may be said to be mainly due to Eddington

in 1930, although he was preceded in 1929 by a paper of Robertson's giving a derivation of a non-static world based on general mathematical assumptions. This was followed in 1930 and 1931 by a series of papers by Tolman, who was led to investigate non-static models from considerations that the transformation of matter into radiation would necessarily lead to a non-static world and thus account for the red-shift. Tolman in the later papers introduced relativistic thermodynamics into the equations with interesting results. Whereas by classical thermodynamics the entropy of a system must increase to a maximum value — all creation at one uniform level of coldness—this is not necessarily the case with relativistic thermodynamics if the cosmical constant is zero or negative. It is then possible to construct models in which, although such irreversible processes as the transformation of matter into radiation might proceed, they might show a continued succession of expansions and contractions of increasing amplitudes without ever reaching the cold death required by classical thermodynamics. But these models are somewhat outside the scope of this review and we shall return to the more strictly astronomical results obtained by Eddington's analysis.

Eddington began working in 1929, with McVittie, to examine whether Einstein's spherical Universe was stable. It seems undoubted that this work was undertaken in the hope of finding an explanation of the red-shift in the nebulae and the velocity-distance relation recently announced by Hubble. Before proceeding very far, however, Lemaitre's work was drawn to his attention. Although not expressly stated in Lemaitre's formulae, it was at once apparent that Einstein's spherical world is unstable, an important fact not hitherto realized. Although Eddington's hope of contributing some definitely new results was thus forestalled, his investigation from the astronomical standpoint is remarkably important and may be said to have inaugurated the new style in cosmogony, the idea of an expanding Universe.

Eddington starts with considerations regarding the value of the cosmical constant λ, which is unknown except as a value can be assigned from astronomical data. Its value, however,

is so small as to be negligible except in the largest-scale applications and is negligible, therefore, in solar system or galaxy. Besides involving λ the form and size of space will depend upon the distribution and amount of the matter in the Universe. On the assumption that the matter is uniformly distributed, approximately true in the part of space observed, space will be spherical and if this Universe is assumed as static there is but one solution, Einstein's Universe. For such equilibrium space must have a particular radius and contain a definite mass, determinate in terms of λ.

However, an infinite variety of solutions can be found representing spherical worlds not in equilibrium. While remaining spherical they expand or contract, the radius being a fraction of the time. One great advance in Eddington's treatment was to show that, even if the spherical world (Einstein's model) was in equilibrium, this was unstable and the slightest disturbance would start it expanding or contracting. Eddington specifically states that there is nothing in the theory to show whether the instability will take the form of expansion or contraction, nor to indicate the rate of change. So far as theory goes, then, it cannot be stated whether the Universe will expand or contract, nor whether such an effect could be observed at nebular distances or whether it might not require distances a million times or more greater. Expansion was chosen and its magnitude determined, only on account of its agreement with the presumed recession of the nebulae, a perfectly legitimate assumption provided that the red-shift of the nebular lines can be unambiguously ascribed to velocity. If due to any other cause, the possibility of which was indicated earlier, then the thesis falls to the ground, and this should be distinctly remembered.

It will be of interest to give some of the numerical data obtained by Eddington on the basis of Hubble's and Humason's results of an increase in apparent velocity of 500 km/sec. for every million parsecs. This corresponds to about 1/2000 of the velocity of light for a distance of a million light-years. That is to say that at a distance of 2,000,000,000 light-years the recessional velocity will have equaled the velocity of light. What happens at greater distances I shall leave the relativist to decide.

Hence the radius of space has expanded by one part in 2000 in the last million years, or the radius has doubled within geological time. This rapid expansion of the Universe is incongruous with the usually accepted time-scale of millions of millions of years for the evolution of stars. The original radius of space, the radius of the Einstein spherical world, depends upon estimates of the density of space and, on the assumption that the density is considerably less than 10^{-28}, the initial radius is of the order of 1,200,000,000 light-years. Eddington states it cannot be calculated how long a period has elapsed from the disturbance of the Einstein equilibrium to the present, but from the time it reached 1.5 times its original radius until the present can scarcely be more than 10,000,000,000 years. The Universe is now doubling its radius every 1,400,000,000 years, and in 10,000,000,000 years the spiral nebulae will be 10 magnitudes fainter than at present. Evidently then, the construction of the 200-inch telescope must be speeded up if any advantage is to be gained and, as Eddington says, astronomers must count themselves fortunate that they are just in time to observe this interesting but evanescent feature of the sky. Finally his theory gives a value of the total mass of the Universe, which should be fairly trustworthy. Since the mass initially formed an Einstein Universe of radius 1,200,000,000 light-years, it is found to be $1.1 \times 10^{22} \odot = 2.3 \times 10^{55}$ gram $= 1.4 \times 10^{79}$ protons.

Eddington's work was the signal for other treatments of the non-static world, of which perhaps the most important were de Sitter's. De Sitter calculated the theoretical course of expansion and contraction for a large number of models, assuming that the transformation of matter into radiation could be neglected. The general trend of his work can best be obtained non-technically by a quotation from a lecture to the Astronomical Society of the Pacific last fall.

> The reason why we thought the Universes of Einstein and de Sitter the only ones was that fifteen years ago we were looking only for static solutions, taking it for granted that the Universe should be a stable structure. If we drop that assumption and think of the Universe as being in course of evolution from one state to another, then there are not only two possible solutions but an infinite number of them. The static

Universe is one extreme having density and no expansion; the empty Universe having expansion and no density is the other extreme. Between these two extremes there is a whole family of solutions of intermediate type having both density and expansion. The actual Universe is one of this family, it started as a static Universe in the past and has since been expanding, until, after an infinite time, it will have reached a state very similar to the empty Universe.

Eddington has recently put forward a new and interesting development of such an expanding Universe, a determination of the rate of expansion, not from measures of red-shift in the nebulae but from an interpretation of the wave-equation containing the mass m of an electron. Eddington says:

Although theory predicts the phenomenon quantitatively, it gives no hint of its scale. So far as relativity theory is concerned we do not know whether the recession will be perceptible within range of our telescopes. . . . . This is a weak point in the claim that the observed recession of the nebulae is actually the theoretically predicted expansion. The observed recession if accepted as genuine is alarmingly rapid, and the consequences in regard to the time-scale of stellar evolution are most startling. For this reason, there has been some disinclination to admit the genuineness of the velocities of the nebulae, and it is suggested that the red-shift of their light has some other explanation. Those who take this view need not dispute the theoretical prediction of an expanding Universe since the theory does not assert the expansion will be rapid enough to detect.

Eddington, therefore, proceeded to determine the constant λ, the velocity-distance effect, the radius, the mass and number of protons in the Universe, and the ratio of the masses of proton and electron from the wave equations of atomic theory, in connection with the curvature of space-time. Briefly, he considers that the ratio of the radius of the normal hydrogen atom, for example, is always a constant fraction of the radius of curvature of space-time associated with that place and direction. The constant λ is equal to $\frac{1}{R^2}$ where R is the radius of an Einstein Universe. Eddington concludes that a term $\frac{\sqrt{N}}{R}$, where N is the number of electrons or protons in the Universe, should appear in the wave-equation. There are a number of terms in the practical wave-equation, but only one

of them is independent of the position of the mobile electron; this term is the natural constant $\frac{mc^2}{e^2}$. Clearly this is the term which must be identified with

$$\frac{\sqrt{N}}{R}, \text{ hence } \frac{\sqrt{N}}{R} = \frac{mc^2}{e^2} \qquad (1)$$

But $\frac{e^2}{mc^2}$ is the constant $b = 2.81 \times 10^{-13}$ cm, regarded as a sort of conventional radius of the atom.

$$\therefore R = b\sqrt{N} \qquad (2)$$

R and N can be found separately from the equations of the Einstein world. Let m be the mass of a proton, then

$$\frac{G\,Nm}{c^2} = \frac{1}{2}\pi R \qquad (3)$$

From equations 2 and 3 he gets

$R = 1.010 \times 10^{27}$ cm $=$ 328,000,000 parsecs $=$ 1,068,000,000 light-years

$M = 2.143 \times 10^{55}$ gm $= 1.08 \times 10^{22}$ $\odot$

$N = 1.29 \times 10^{79}$

$P = 1.05 \times 10^{-27}$ gm/cm^3

The speed of recession of distant objects is $c/R\sqrt{3}$ which gives 527.8 km/sec. for every million parsecs. The value of the constant λ which is $1/R^2$ becomes 9.8×10^{-55} cm^{-2}. Eddington interpolates some remarks in regard to the constant λ which, in view of more recent developments, should be quoted:

> The cosmical constant λ occurs in Einstein's law of gravitation $G\mu\nu = \lambda g\mu\nu$. In the resulting equation of motion the term represents a scattering force which tends to make all bodies recede from one another. . . . . The repulsion may be to some extent counterbalanced by the ordinary gravitational attraction of the nebulae on one another.

When the Universe has so far expanded that this gravitational attraction becomes negligible, the distances of the galaxies double themselves in $\frac{R\sqrt{3}}{c}$, or 1,280,000,000 years.

Finally, Eddington deduces the theoretical relation of proton to electron, and the ratio of their masses is found to be 1847.6, very close to the observed values. The differences between all these values and the earlier ones are due to the difference between the observed and calculated values of the velocity distance relation 500 and 527.8 km/sec. per million parsecs.

Eddington concludes with a characteristic word of caution:

> I do not want to stress too much the accuracy or finality of these results. I cannot see how anything can be possibly wrong with them, but then one never does see these faults until some new circumstances arise or some ingenious person comes forward to show us how blind we have been.

This theoretical structure of Eddington is a very beautiful and complete piece of work and should be of especial interest to astronomers as it gives an entirely new theoretical method of obtaining, for example, the much disputed position of the zero point in the period luminosity curve of *Cepheids*. Unfortunately, however, though no one has criticized the superstructure, there have been two serious attacks on the foundations, one by Einstein and the second by Einstein and de Sitter.

Einstein in a recent paper before the Berlin Academy has pointed out that it is no longer necessary to retain λ in the field equations. It was previously required with the static Universe, as without it the equations gave a negative pressure for a positive uniform density of matter. If the Universe is not static Einstein has shown that there can be a positive uniform density with zero pressure for zero values of λ, and he proposes, therefore, to drop the λ term from the field equations. As we have already seen, Eddington states that the λ term represents a scattering force, which tends to make all bodies recede from one another. While these two statements may not be irreconcilable, there is certainly some difficulty about this particular building block.

The second attack on the foundations of Eddington's theoretical determination of the dimensions of the Universe has just appeared in the *Proceedings of the National Academy of Sciences* in a paper by Einstein and de Sitter. It would scarcely be out of place to liken them to Samson pulling down the pillars

of the temple, although unlike Samson they escaped the ruins by departing from the country. Seriously, however, this paper must have a definite reaction on all previous models of the Universe, which have all assumed positive curvature of space-time. Hickmann has recently pointed out that the non-static solutions of the field equations with constant density do not necessarily imply positive curvature of three-dimensional space, which may also be negative or zero. Einstein and de Sitter state there is no direct observational evidence of the curvature, the only observed data being the mean density and the expansion. The question then arises whether it is possible to represent the observed facts without introducing any curvature. They, therefore, proceed to examine the results on the field equations of assuming the curvature to be zero. The equations then reduce to simple forms and the dimensions of space can be easily calculated. Taking the velocity-distance relation as $h = 500$ km/sec. per million parsecs, the density comes out on the assumption of zero curvature as $p = 4.10^{-28}$ gm/cm^3. This coincides exactly with the upper limit of density assumed by de Sitter and corresponds, on the assumption that there is no matter in intergalactic space, to galaxies separated by distances of one million light-years and having masses of 2×10^{11} suns, about Oort's estimate of the mass of the galaxy. They say in conclusion: "Although, therefore, the density corresponding to the assumption of zero curvature and to the above coefficient of expansion may perhaps be on the high side, it certainly is of the correct order of magnitude, and we must conclude that at the present time it is possible to represent the facts without assuming a curvature of three-dimensional space." As Eddington's theoretical dimensions were obtained on the assumption of a positive curvature of space-time, you will have to ask someone besides an astronomer what happens when the curvature is zero.

And these examples by no means exhaust the difficulties and contradictions occasioned by different interpretations and assumptions. Eddington and Tolman hold diametrically opposite views on the effect that the transformation of matter into radiation will have on inducing a change of dimensions in the Universe, while McRae and McVittie on the one hand and Lemaitre

on the other equally disagree on the effect of the formation of condensations on the expansion or contraction of the Universe.

Amid such theoretical confusion the astronomer may happily restrict himself to the firm conviction that the nebular red-shift is approximately proportional to distance, and to the attempt to increase the accuracy of the determinations of the density of space. He may, by these latest developments, feel reasonably assured that the space to the limits to which he can observe is Euclidean and that he need not worry about the curvature of space-time.